Common magnitude representation of fractions and decimals is task dependent

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Abstract

Although several studies have compared the representation of fractions and decimals, no study has investigated whether fractions and decimals, as two types of rational numbers, share a common representation of magnitude. The current study aimed to answer the question of whether fractions and decimals share a common representation of magnitude and whether the answer is influenced by task paradigms. We included two different number pairs which were presented sequentially: fraction–decimal mixed pairs and decimal–fraction mixed pairs in all four experiments. Results showed that when the mixed pairs were very close numerically with the distance 0.1 or 0.3, there was a significant distance effect in the comparison task but not in the matching task. However, when the mixed pairs were further apart numerically with the distance 0.3 or 1.3, the distance effect appeared in the matching task regardless of the specific stimuli. We conclude that magnitudes of fractions and decimals can be represented in a common manner, but how they are represented is dependent on the given task. Fractions and decimals could be translated into a common representation of magnitude in the numerical comparison task. In the numerical matching task, fractions and decimals also shared a common representation. However, both of them were represented coarsely, leading to a weak distance effect. Specifically, fractions and decimals produced a significant distance effect only when the numerical distance was larger.

Keywords: fraction representation; decimal representation; numerical comparison task; numerical matching task; numerical distance effect

1. Introduction

In recent years, there has been a rapid increase in cognitive studies about the processing and representation of fractions and decimals, which are two types of rational numbers (e.g., Bonato, Fabbri, Umiltà, & Zorzi, 2007; DeWolf, Grounds, Bassok & Holyoak, 2014; Ganor-Stern, 2012, 2013; Ganor-Stern, Karasik-Rivkin, & Tzelgov, 2011; Ischebeck, Schocke, & Delazer, 2009; Jacob & Nieder, 2009; Kallai & Tzelgov, 2009, 2014; Meert, Grégoire, & Noël, 2009, 2010). Typically, these studies have focused on the respective processing of fractions and decimals by examining the extent to which the mental representation of fractions or decimals is the same as or different from representations of integers. Although several studies have compared the representation of fractions and decimals, no study has investigated whether fractions and decimals, as two types of rational numbers, share a common representation of magnitude. The current study aimed to answer the question of whether fractions and decimals share a common representation of magnitude and whether the answer is influenced by task paradigms.

A particularly well researched potential marker of the magnitude representation of natural numbers is the so-called numerical distance effect, which means that close magnitudes (or numbers) are harder (slower and more error prone) to compare than distant magnitudes (e.g. comparing 1 vs. 5 is faster and more accurate than comparing 1 vs. 2; Moyer & Landauer, 1967). The distance effect is often seen as evidence for the mental number line metaphor which assume that numbers are represented along an analog mental number line (Restle, 1970). So far, this effect has been shown repeatedly with natural numbers, but has only been recently investigated with complex rational numbers, especially fractions and decimals (e.g., Ganor-Stern, 2013; Kallai & Tzelgov, 2009; Schneider & Siegler, 2010).

Fractions, written in the symbolic form a/b, play a crucial role in children's mathematical development (Bailey, Hoard, Nugent, & Geary, 2012; Siegler et al., 2012). Therefore, numerous studies have investigated how fractions are represented. The main concern is the question of whether the representation of fraction is holistic or componential. The processing of fractions is said to be holistic when it relies on the whole magnitude of fractions, but componential when relying on the constituent numerator or denominator (Ischebeck et al., 2009).

Some studies have addressed the question by examining the presence of a distance effect in comparisons of fraction pairs (e.g., Bonato et al., 2007; DeWolf & Vosniadou, 2014; Faulkenberry & Pierce, 2011; Huber, Moeller, & Nuerk, 2014; Meert et al., 2009, 2010; Schneider & Siegler, 2010; Zhang, Xin, Li, Ding, & Li, 2012). For example, Bonato et al. (2007) asked participants to compare a standard fraction 1/5 with fractions with the common numerator 1(e.g., 1/2, 1/6). Results showed the denominator distance effect appeared while the holistic magnitude distance effect did not. They concluded that the holistic numerical value of the fraction was not accessed and fractions were processed componentially. However, when comparing pairs of fractions without common components, Schneider and Siegler (2010) found that college students exhibited a distance effect between the holistic magnitudes of fractions. Other studies have examined the representation of fractions by examining the presence of a distance effect when comparing of a fraction with a whole number (Ganor-Stern, 2012, 2013; Kallai & Tzelgov, 2009). Using a numerical comparison task, the study by Kallai and Tzelgov (2009) revealed that the distance effect for mixed pairs composed of a natural number and a fraction (e.g., 5 vs. 1/4) was associated with the natural numbers involved in the pairs, while the different fractions perceived as a constant value smaller than one. Using a stroop-like physical comparison task (where the numerical magnitude is irrelevant to task demand), they found faster RTs in the incongruent condition (e.g., 1/3, 1/5) compared with the congruent condition (e.g. 1/3, 1/5). .It was concluded that the componential magnitude rather than the holistic magnitude of fractions is automatically accessed. In addition, one study has examined the representations of fractions in physical and numerical matching tasks in which adults decided whether two fractions equaled each other physically or numerically (Gabriel et al., 2013a). Results showed that participants could access the holistic magnitude of fractions only in the numerical matching task.

In contrast to abundant studies of fractions, only a few studies have investigated the mental representation of decimals (Cohen, 2010; Huber, Klein, Willmes, Nuerk, & Moeller, 2014; Kallai & Tzelgov, 2014; Varma & Karl, 2013; Zhang, Chen, Lin, & Szűcs, 2014). These studies have addressed whether the representation of decimals is similar to that of multi-digit integers by examining the distance effect and/or the compatibility effect. The compatibility effect refers to the fact that unit-decade compatible number pairs (e.g., for 52–78, both 5 < 7 and 2 < 8) are responded to faster and more accurately than unit-decade incompatible pairs (e.g., for 52–47, 5 > 4 but 2 < 7) (Nuerk, Weger, & Willmes, 2001). This effect is a main maker for the componential processing of multi-digit numbers. By examining the distance effect and/or the compatibility effect, most researchers showed that the representation of decimals is different from representation of integers. For example, Cohen (2010) compared the processing of two-digit integers and decimals between 0 and 1 in numerical comparison tasks. Their data revealed that the numerical distance is the primary variable controlling participants' RTs for the comparison of integers. However, the physical similarity between the tenth place of the standard and the probe is the primary variable controlling participants' RTs for the comparison of decimals.

Using the automatic processing paradigm where the numerical magnitude of decimals is task-irrelevant, Kallai and Tzegov (2014) showed that decimals are not represented well enough to be automatically activated as integers. In addition, three studies observed a smaller compatibility effect for decimals than for integers (Huber et al., 2014; Varma & Karl, 2013; Zhang et al., 2014).

Until recently, several studies compared the processing of decimals and fractions. As rational numbers, fractions and decimals differ in two ways. First, their superficial expressions are greatly different. Fractions in the form a/b have an upper-lower structure with two numbers and a line which expresses a relation between two integers. In contrast, decimals have a left-right structure with two numbers and a decimal mark which expresses the magnitude of that relation (DeWolf, Bassok, & Holyoak, 2015). Second, their teaching in mathematical classroom is also different. When teaching fractions, teachers often use area models and emphasize the part–whole concept (e.g., a pie is cut into five equal pieces) and collection models (e.g., one blue ball and four red balls in a group of five balls). When teaching decimal fractions, by contrast, teachers often use a ruler (1.3 m = 1 m and 30 cm) or money ($1.11 = 1 dollar, 1 dimes, and 1 penny). As such, a fraction is inherently a two-dimensional structure because both the numerator and the denominator are free to vary, whereas a decimal is inherently one-dimensional and static with the fixed and implied denominator 10 (DeWolf, Bassok, & Holyoak, 2015). Therefore, most previous studies have showed their different processing. Iuculano and Butterworth (2011) asked participants to complete two tasks: mark the line to indicate the target number and estimate the numerical value of a mark on the line. Their results indicated that decimals and integers demonstrated a linear representation in both tasks, but a linear representation can be only observed when participants were asked to place a fractional value on a line. Using a comparison task, Ganor-Stern (2013) included mixed pairs of a unit fraction and a natural number, and of a decimal and a natural number. Results showed that the distance effect appeared for mixed pairs of a decimal and a natural number but not for mixed pairs of a unit fraction and a natural number. It was concluded that there was an easier mapping of decimals on the same mental number line with integers as compared to unit fractions. In the study by Zhang et al., (2013), participants were asked to match decimals or fractions with non-symbolic ratios. The results showed that it was more difficult for matching fractions and non-symbolic ratios than for matching decimals and non-symbolic ratios. DeWolf et al. (2014) compared the processing of fractions and decimals. The distance effect was found for both, but it was stronger for fractions than decimals. It was concluded that the magnitude values associated with fractions appear to be less precise than decimals. Above studies reveal easier processing of decimals than fractions. Recently, one study (DeWolf, Bassok, & Holyoak, 2015) has showed that fractions are relatively advantageous in supporting relational reasoning with discrete () or discretized display () relative to continuous display ().

The present study broadens the existing research in two ways. First, we examined whether fractions and decimals share a common representation of magnitude. Although previous studies have compared the representation of fractions and decimals, no study has addressed the connections between fractions and decimals. Specifically, it is unclear whether fractions and decimals are converted to a common representation of magnitude when they are numerically compared or matched with each other. Recent studies have explored whether there is a common representation of magnitude in different symbols of integers (i.e., Arabic vs. verbal numerals) (Cohen Kadosh et al., 2007; Dehaene & Akhavein, 1995; Ganor-Stern & Tzelgov, 2008; 2011). However, no study has addressed this question with fractions and decimals. As two main types of rational numbers, fractions and decimals connect with the same semantic system. They can be transformed into each other. For example, 3/10 = 0.3, which means three shares of a whole divided into 10. Therefore, the use of fractions and decimals would allow us to explore the question of whether there is common processing for different formats of rational numbers. The investigation of this question is theoretically important since it can test the integrated theory of number development (Siegler, Thompson, & Schneider, 2011). This theory emphasizes the continuity between the acquisition of knowledge on all types of real numbers which have magnitudes that can be ordered and assigned specific locations on number lines (Siegler et al., 2013). If fractions and decimals are converted into a common representation of magnitude, it will provide support for the integrated theory.

Second, we investigated the representation of fractions and decimals using two experimental paradigms: numerical comparison and matching tasks. It is said that the matching and comparison tasks, although similar, each provide a unique piece of information. The comparison task is argued to measure the intentional processing of number while the matching task is to measure the automatic processing of number (Goldfarb et al., 2011). In addition, Ganor-Stern and Tzelgov (2008) propose that the comparison task provides information on the numbers cardinality, whereas the former provides information about the numbers ordinality. In the current study, therefore, use of both tasks can enhance the generality of our results. In both tasks, we included two different number pairs: fraction–decimal mixed pairs and decimal–fraction mixed pairs. If the numerical distance effect appears in either number pair, we can infer that there is a common representation for different formats of rational numbers.

We have conducted four experiments. In Experiment 1 and 2, with the distance effect as an indication of the magnitude representation, we examined the representation of fractions and decimals in numerical comparison and matching tasks. The distance between the stimuli could either be small (an average of 0.10) or large (an average of 0.30). Experiment 3 manipulated the distance to examine whether the distance effect would appear in the numerical matching task when the large and small distances became further apart. The small distance pairs (an average of 0.30) were identical to the large distance pairs in Experiment 1 and 2 (e.g., 2/5 and 0.7). However, the large distance had an average of 1.30 (e.g., 2/5 and 1.7). Experiment 4 manipulated stimuli characteristics to examine whether the distance effect was affected by stimuli characteristics in the numerical matching task.

2. Experiment 1

In Experiment 1, we examined the representation of fractions by using a numerical comparison task. For the first time, fractions and decimals were presented in mixed pairs.

2.1 Method

2.1.1 Participants

Twenty-one Chinese students from Southwest University, Chongqing, China participated in the experiment. Their ages ranged from 19 to 24 years (mean age = 21.6 years; *SD* = 1.2; 16 females and 5 males). All had normal or corrected-to-normal vision with no reading or mathematical deficits. After the experiment, each participant was paid RMB 10 yuan.

2.1.2 Materials and design

A total of 60 experimental pairs were constructed. These number pairs varied in the level of distance and order. In terms of distance level, two categories of numerical distances were included: small distance pairs with an average numerical difference of 0.10 (from 0.03 to 0.17); and large distance pairs with an average numerical difference of 0.30 (from0.23 to 0.38). Some numbers greater than 1 were also included in stimuli set in order to create enough number pairs. In terms of order level, two types of pairs were used: a fraction was presented before a decimal and a decimal was presented before a fraction. Each distance in each order was composed of 15 number pairs (see Table 1), thus creating a total of 60 trials (15 pairs × 2 distances × 2 orders). These trials were repeated three times.

2.1.3 Procedure

Participants were asked to decide which was bigger between the two numbers successively presented on the screen. Stimuli were presented sequentially to ensure that subjects processed the first number and kept it in their short-term memory before they attempted to compare it with the second number. Previous studies have revealed the important influence of presentation mode on the number processing (Ganor-Stern, Pinhas, & Tzegov, 2009; García-Orza, & Damas, 2011; Moeller, Klein, Nuerk, Willmes, 2013; Zhang & Wang, 2005; Zhou, Chen, Chen, & Dong, 2008). This study aimed to offer the picture with respect to the numerical representation involved in the comparison of rational numbers, where one is held in memory. Sequential presentation also eliminated the need for participants to saccade back and forth between stimuli when making comparison judgments since fractions and decimals differ greatly in their surface structure. One half of participants pressed the “F” key if the number first presented was bigger and pressed the “J” key if the number second presented was bigger. The other half of participants pressed the “F” key if the number second presented was bigger and pressed the “J” key if the number first presented was bigger. All the stimuli were randomly presented.

Participants completed the numerical comparison task individually in a small, sound attenuated room, seated approximately 60 cm from the computer screen. All the stimuli were presented visually in black, Times New Roman, 28 points on a white background at the center of a 19 inch 800 × 600 pixel color monitor with a 75 Hz refresh rate.

Each trial started with a black fixation cross (+) in the middle of the screen for 500 ms. Then the first digit was presented for a period of 600 ms, which was followed by a blank screen for 100 ms. Finally, the second digit was presented in the center of the screen until a response was given or until 2000 ms had elapsed. After an interval of 1500 ms, the next trial began. The stimuli in Experiment 1 are listed in Table 1.

Table 1 about here

2.1.4 Data analysis

For RTs analyses, all incorrect responses were removed. Scores more than three standard deviations from mean were excluded as outliers. Then, the average RTs for each participant in each condition was calculated. The data were subjected to a repeated-measures ANOVA with distance (small vs. large) and order (fraction first vs. decimal first) as within-subject factors.

2.2 Results

Figure 1 shows the accuracy and RTs in each condition in Experiment 1. The ANOVA on accuracy revealed a significant main effect of distance, F (1, 20) = 31.347, p <.001, η^2 = .610. The accuracy for the large distance (93.0%) was higher than that for the small distance (87.8%). In order to confirm the effect size of distance we computed Cohens' *d*. Cohens' $d = M_1 - M_2 / s_{pooled}$ where $s_{pooled} = \sqrt{[(s_1^2 + s_2^2) / 2]}$. Effect sizes of 0.2 are defined as small, 0.5 defined as moderate, and 0.8 defined as large (Cohen, 1988). In this study, the Cohens'*d* = 1.153, indicating that the two distance means largely differed. The main effect of order (p =.062) and the interaction (p =.527) were not significant.

Figure 1 about here

The ANOVA on RTs revealed a significant main effect of distance, F (1, 20) = 15.793, p = .001, η^2 = .441. The RTs for the large distance was shorter (904ms) than that for the small distance (972ms). The Cohens'*d* = .323, indicating that the two distance means differed in an accepted degree. The main effect of order was also significant, F (1, 20) = 97.165, p < .001, η^2 = .829. Responses for fraction first (853ms) were faster than those for decimal first (1023ms). The Cohens'*d* = .804, indicating that the two order means largely differed. The interaction (p =.280) was not significant.

2.4 Discussion

The presence of the distance effect in both RTs and accuracy analyses suggests that participants translated fractions and decimals into a common representation of magnitude in the numerical comparison task. Furthermore, this experiment demonstrated that when a fraction was presented before a decimal, RTs (853ms) were shorter than when a decimal was presented before a fraction (1023ms). It is likely that participants finished the comparison by transforming a fraction into a decimal[1]. When a fraction was presented first, it was transformed into a decimal format before the following decimal appeared. However, when a decimal was presented first, the transforming process could only occur after the following fraction appeared. Accordingly, the difference of RTs (170ms) reflected the process of transformation of a fraction (e.g., 1/5) into a decimal (e.g., 0.2) when the decimal was presented before a fraction. Kerslake (1991) has proposed that the system of decimals is so eminently simple that when it is generally understood it will entirely displace the clumsy system of fractions. As such, fractions tend to be transformed into decimals.

3 Experiment 2

Experiment 1 revealed that fractions and decimals were translated into a common representation of magnitude. However, it is unclear whether such finding depends on task paradigms. This experiment aimed to address this question by using a numerical matching task.

3.1 Method

3.1.1 Participants

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1 We performed one numerical comparison experiment mixing four stimuli types (fraction/fraction pairs, decimal/decimal pairs, fraction/decimal pairs, and decimal/fraction pairs). Results showed that the comparison performance in measures of RTs and accuracy for decimal/decimal pairs were better than any of other three types (*ps* <.001). Accuracy for fraction/decimal pairs was higher than fraction/fraction pairs (p =.057). Accuracy for decimal/fraction pairs did not differ from those for fraction/fraction and fraction/decimal pairs (*p*s > .126). Responses for fraction/decimal pairs were faster than for fraction/fraction and decimal/fraction pairs (*ps* <.001). Responses for fraction/fraction pairs did not differ from those for decimal/fraction pairs (p = 1.000). These findings showed that a decimal is more easily processed than a fraction and that fractions are likely to be transformed into decimals.

Twenty-one Chinese students from Southwest University, Chongqing, China participated in the experiment. Their ages ranged from 19 to 26 years (mean age = 22.3 years; *SD* = 1.4; 18 females and 3 males). All had normal or corrected-to-normal vision with no reading or mathematical deficits. After the experiment, each participant was paid RMB 10 yuan. No participant took part in Experiment 1.

3.1.2 Materials and design

All the experimental pairs were identical to those in Experiment 1, but in this Experiment, they were only presented once. In addition, sixty filler pairs with a numerical difference of 0 were constructed to balance “different” and “same” responses. The performance of each participant for these filler pairs was not analyzed.

3.1.3 Procedure

The procedure was identical to the one of Experiment 1 except for the instructions. Participants were asked to decide whether the two numbers successively presented on the screen were equal in their numerical magnitude. One half of participants pressed the “F” key if the numbers were equal and pressed the “J” key if the numbers were not equal. The other half of participants pressed the “J” key if the numbers were equal and pressed the “F” key if the numbers were not equal. Stimuli were randomly presented.

3.1.4 Data analysis

Two participants were excluded because their accuracy was lower than 80%. For RTs analyses, all incorrect responses were removed. Scores more than three standard deviations from mean were excluded as outliers. Then, the average RTs for each participant in each condition was calculated. The data were subjected to a repeated-measures ANOVA with distance (small vs. large) and order (fraction first vs. decimal first) as within-subject factors.

3.2 Results

Figure 2 shows the accuracy and RTs in each condition in Experiment 2. The ANOVA on accuracy revealed a significant main effect of order, F (1, 18) = 6.603, p =.024, η^2 = .252. The accuracy for fraction first was higher (94.7%) than that for decimal fractions (92.5%). Cohens' d = 0.573, indicating that the two order means differed in a medium degree. The main effect of distance (p =.074) and the interaction (p =.191) were not significant.

Figure 2 about here

The ANOVA on RTs revealed only a significant main effect of order, F (1, 18) = 72.557, p < .001, η^2 = .801. Responses for fraction first (702ms) were faster than those for decimal first (849ms). Cohens' d = 1.008, indicating that the two orders means largely differed. The main effect of distance (p =.107) and interaction (p =.244) was not significant.

Finally, in order to directly compare the performance of participants in numerical comparison and matching tasks, we conducted combination analyses of Experiments 1 and 2. The data were subjected to repeated measure ANOVAs with distance (small vs. large) and order (fraction first vs. decimal first) as within-subject factors while task (comparison vs. matching) as a between-subject factor.

The accuracy analysis revealed a significant main effect of order, F (1, 38) = 167.992, p < .001, η^2 = .816, and a significant interaction of task × distance, F (1, 38) = 17.194, p < .001, η^2 = .312. The main effect of distance was also significant, F (1, 38) = 4.982, p = .032, η^2 = .116. All other interactions were not significant (*ps* >.108). The simple effect analyses confirmed that the interaction was due to the distance effect which was significant in the comparison task, F (1, 20) = 31.347, p < .001, η^2 = .610, but not in the matching task (p =.074).

Similarly, the RTs analysis revealed a significant main effect of order, F (1, 38) = 9.345, p = .004, η^2 = .197, and a significant interaction of task × distance, F (1, 38) = 19.827, p < .001, η^2 = .343. The main effect of distance and other interactions were not significant (*ps* >.142). The simple effect analyses confirmed that the interaction was due to that the distance effect was significant in the comparison task, F (1, 20) = 15.793, p < .001, η^2 = .441, but not in the matching task (p =.107).

3.3 Discussion

This experiment did not show explicit evidence for a common representation of magnitude shared by fractions and decimals in the matching task because the distance effect did not appear. We conclude that the common magnitude representation of fractions and decimals depends on task paradigms. In this study, it is less likely that participants made their judgments for all number pairs according to the physical features of stimuli. The superficial structures of fractions and decimals are vastly different. Therefore, participants should have made judgments by accessing the numerical magnitudes of stimuli. Indeed, in spite of no distance effect, this experiment revealed a significant order effect. It is likely that participants accessed the holistic magnitude of fractions by transforming a fraction into a decimal. The absence of the distance effect may be associated with the fact that there is only a coarse representation of magnitude in the matching task which leads to a weak distance effect. We conducted Experiment 3 to test this hypothesis.

4 Experiment 3

In Experiment 2, no distance effect was observed. We hypothesized that there is only a coarse representation of magnitude in the matching task. Therefore, when the number pairs to be matched were very close numerically, the distance effect did not appear, as revealed in Experiment 2. However, if the number pairs to be matched are far apart numerically, the distance effect may appear. To test this possibility, in Experiment 3, we made our number pairs further apart numerically by increasing the small distance to 0.3 and the large distance to 1.3.

4.1 Methods

4.1.1 Participants

Twenty Chinese students from Southwest University, Chongqing, China participated in the experiment. Their ages ranged from 19 to 24 years (mean age = 21.6 years; *SD* = 1.4; 17 females and 3 males). None of these participants took part in Experiments 1 and 2.

4.1.2 Materials and design

As in Experiment 1, there were 60 experimental trials (15 pairs × 2 distances × 2 orders). A total of 15 close distance pairs with an average numerical difference of 0.30 (from 0.23 to 0.38) were identical to the large distance number pairs in Experiment 1. The 15 large distance pairs had an average numerical difference of 1.30 (from1.23 to 1.38). In addition, sixty filler pairs were also identical to those in Experiment 2.

4.1.3 Data analysis

Two participants whose accuracy was lower than 80% were excluded. Similarly, all incorrect responses were removed for RTs analyses and scores more than three standard deviations from mean were excluded as outliers. The data were subjected to a repeated-measures ANOVA with distance (small vs. large) and order (fraction first vs. decimal first) as within-subject factors.

In order to test the influence of context on the processing of numbers, repeated-measures ANOVAs were also conducted with order (fraction first vs. decimal first) as a within-subject factor and experiment (Experiment 2 vs. 3) as a between-subject factor. These analyses only focused on the number pairs with an average numerical difference of 0.30 (from 0.23 to 0.38), which were defined a large distance in Experiment 3 and a small distance in Experiment 2.

4.1.4 Procedure

The procedure was identical to the one in Experiment 2.

4.2 Results

Figure 3 shows the accuracy and RTs in each condition in Experiment 3. The ANOVA on accuracy revealed a significant main effect of order, F (1, 17) = 16.896, p =.016, η^2 = .498. The accuracy for fraction first (96.3%) was higher than when decimals were presented first (92.0%). Cohens'd = 0.892, indicating that the two order accuracy means largely differed. The main effect of distance was significant, F (1, 17) = 14.494, p =.001, η^2 = .460, with higher accuracy for the large distance (97.0%) than for the small distance (91.2%). Cohens'd = 1.091, indicating that the two distance accuracy means largely differed. The interaction was not significant (p=.267).

Insert Figure 3 about here

The ANOVA on RTs revealed only a significant main effect of order, F (1, 17) = 38.965, p <.001, η^2 = .696. The RTs for fraction first (591 ms) was shorter than when decimals were presented first (663 ms). Cohens'd = 0.571, indicating that the two order RTs means differed in a medium degree. The main effect of distance was significant, F (1, 17) = 31.688, p <.001, η^2 = .651, with shorter RTs for the large distance (608 ms) than for the small distance (646). Cohens'd = 0.305, indicating that the two distance RTs means differed in an acceptable degree. The interaction was not significant (p=.107).

In addition, ANOVA on accuracy with order (fraction first vs. decimal first) as a within-subject factor and experiment (Experiment 2 vs. 3) as a between-subject factor showed that only the order main effect was significant, F (1, 17) = 19.103, p <.001, η^2 = .353. The accuracy for fraction first (92.1%) was higher than when decimals were presented first (91.2%). Cohens'd = 0.704, indicating that the two order accuracy means differed in a medium degree. The main effect of experiment (p =. 667) and the interaction (p =.499) was not significant.

Analyses on RTs showed that there was significant effect of order, F (1, 35) = 90.214, p <.001, η^2 = .720, and of experiment, F (1, 35) = 10.178, p =.003, η^2 = .225. The RTs for fraction first (652 ms) was shorter than when decimals were presented first (779ms). The RTs for Experiment 2 (786 ms) was longer than those for Experiment 3(646 ms). The interaction was also significant, F (1, 35) = 7.061, p =.012, η^2 = .168. Follow up analyses showed the effect of experiment was significant for both fraction first order, t(35) = 2.414, p =.021, and decimal first order, t(35) = 3.630, p =.001. The interaction was due to that the experiment differences was stronger for decimal first (175ms, Cohens'd = 1.194) than for fraction first (95ms, Cohens'd = 0.797).

4.3 Discussion

Consistent with Experiments 1 and 2, we found a main effect of order. Number pairs with fractions before decimals were responded to faster and more accurately than those with decimals before fractions. More importantly, as revealed by the significant distance effect, this experiment demonstrated explicit evidence for that fractions and decimals were converted into a common representation of magnitude.

However, one possibility for the appearance of the distance effect in Experiment 3 is that participants did not accurately access the holistic magnitude of fractions and decimals in the “large” distance pairs, but merely evaluated and classified them as smaller or larger than 1. For example, in the large distance pair (2/5 and 1.7), 2/5 was likely to be classified as smaller than 1 whereas 1.7 was classified as larger than 1. After doing so, the matching judgment could be made faster. In contrast, the two numbers in the small distance pairs (e.g., 2/5 and 0.7) fell on the same sides of 1, that is, smaller than 1. The matching judgment of the small distance pairs could not be made by classifying, but had to be made by accurately representing the holistic magnitude of stimuli. As a result, the performance for the large distance pairs was possibly better than for the small distance pairs, resulting in the appearance of the distance effect. We designed Experiment 4 to test this possibility.

It is interesting that this experiment also revealed the influence of context on the processing of number. When number pairs with a numerical distance of 0.30 were mixed by pairs with a numerical distance of 0.10 as in Experiment 2, they were responded to more slowly than when mixed by pairs with a numerical distance of 1.30 as in Experiment 3. We would discuss the implication of this finding in General discussion.

5 Experiment 4

The significant distance effect in Experiment 3 showed that fractions and decimals were converted into a common representation of magnitude. However, the distance effect in Experiment 3 may have come from the fact that the two numbers in the “large” distance pairs spanned across 1. In order to investigate this possibility, we conducted Experiment 4 where both the small distance pairs and the large distance pairs spanned across 1. If the distance effect disappears in this experiment, it would suggest that the distance effect in Experiment 3 is associated with the specific stimuli. However, if the distance effect persists, it would suggest that the distance effect in Experiment 3 is truly due to the larger numerical distance.

5.1 Methods

5.1.1 Participants

Twenty-two Chinese students from Southwest University, Chongqing, China participated in the experiment. Their ages ranged from 18 to 25 years (mean age = 21.5 years; *SD* = 2.2; 17 females and 5 males). None of these participants took part in Experiments 1, 2 and 3.

5.1.2 Materials and design

Similarly, there were 60 experimental trials (15 pairs × 2 distances × 2 orders). The 15 large distance pairs with an average numerical difference of 1.30 (from 1.23 to 1.38) were identical to Experiment 2. The 15 small distance pairs had an average numerical difference of 0.32 (from 0.24 to 0.45). Furthermore, the two numbers in the small distance pairs fell on different sides of 1. For example, in the pair 6/5 and 0.8, 6/5 is bigger than 1 whereas 0.8 is smaller than 1. In addition, sixty filler pairs were identical to Experiment 2, and were not analyzed. The procedure was identical to the one in Experiment 2.

5.3 Results

Two participants were excluded because their accuracy was lower than 80%. Similarly, all incorrect responses were removed for RTs analyses and scores more than three standard deviations from mean were excluded as outliers.

Figure 4 shows the accuracy and RTs in each condition in Experiment 4. The ANOVA on accuracy revealed a significant main effect of distance, F (1, 19) = 7.958, p =.011, η^2 = .295, with higher accuracy for the large distance (95.8%) than for the small distance (91.4%). Cohens'*d* = 0.873, indicating that the two distance accuracy means largely differed. The interaction of distance × order was not significant (p=.270) and the main effect of order was not significant (p=.089).

Figure 4 about here

The ANOVA on RTs revealed a significant main effect of order, F (1, 19) = 49.186, p <.001, η^2 = .721. The RTs for fraction first (619 ms) was shorter than when decimals were presented first (704 ms). Cohens'*d* = 0.759, indicating that the two order RTs means differed in a medium degree. The main effect of distance was significant, F (1, 19) = 12.535, p =.002, η^2 = .397, with shorter RTs for the large distance (638 ms) than for the small distance (685 ms). Cohens'*d* = 0.417, indicating that the two distance RTs means differed in an acceptable degree. The interaction was marginally significant, F (1, 19) = 3.998, p =.060, η^2 = .174. Follow up analyses showed that the interaction was due to a significant distance effect for decimal first, t(20) = 3.287, p =.004, but not for fraction first (p =.101). Furthermore, when decimals were presented before fractions, Cohens'*d* = 0.543 for the distance effect, indicating that the two distance RTs means differed in a medium degree.

In addition, ANOVA on accuracy with order (fraction first vs. decimal first) as a within-subject factor and experiment (Experiment 3 vs. 4) as a between-subject factor only revealed a significant order effect, F (1, 36) = 5.635, p =.023, η^2 = .135. The accuracy for fraction first (97.4%) was higher than when decimals were presented first (95.4%). Cohens'*d* = 0.358, indicating that the two order accuracy means differed in an accepted degree. The main effect of experiment (p =. 415) and the interaction (p =.232) were not significant.

Analyses on RTs showed that there was a significant effect of order, F (1, 36) = 28.723, p <.001, η^2 = .444. The RTs for fraction first (594 ms) was shorter than when decimals were presented first (652 ms). Cohens'd = 0.474, indicating that the two order RTs means differed in an accepted degree. The main effect of experiment (p=.427) and the interaction was not significant (p =.738).

5.4 Discussion

The results of Experiment 4 are in line with the results of Experiment 3. As with Experiment 3, stimuli pairs with decimals presented before fractions produced a significant distance effect in both RTs and accuracy analyses. For pairs with fractions presented before decimals, the error rates also showed the distance effect. Although the RTs analysis did not show a significant distance effect, the descriptive statistics showed a potential tendency (in Figure. 4). In Experiment 4, the number pairs for both distances were set so they spanned across 1. As the distance effect was still observed, we conclude that the distance effect in Experiment 3 was due to the larger numerical distance rather than specific stimuli.

In addition, our analyses showed that the performance of number pairs with a numerical distance of 1.30 did not differ between Experiments 3 and 4. In both Experiments 3 and 4, the small distance was 0.3 and large distance was 1.3. Combining the results of Experiments 3 and 4, it seems that the influence of context is not related to specific numbers in a number pair but the numerical distance between the two numbers in a pair.

6. General Discussion

The main question posed by the present study was whether fractions and decimals, as two types of rational numbers, share a common representation of magnitude. On the basis of participants' responses on mixed–notation pairs in both numerical comparison and matching tasks, we found that the answer depends on task paradigms. In the numerical comparison task, fractions and decimals shared a common representation of magnitude, as indicated by the significant numerical distance effect. In the numerical matching task, fractions and decimals also shared a common representation. However, both of them were represented coarsely, leading to a weak distance effect. Specifically, fractions and decimals produced a significant distance effect only when the numerical distance was larger.

The distance effect appeared when fractions were compared to decimals as revealed in Experiment 1. This important finding gave evidence that numerals in either fraction or decimal notation are converted to a common magnitude representation, which provides support for the integrated theory of number development (Siegler, Thompson, & Schneider, 2011). To take it one step further, we assume that participants finished the comparison by transforming a fraction into a decimal. In other words, the holistic representation of fractions was activated. On the one hand, it is unlikely that participants translated a decimal to a fraction. As Experiment 1 revealed, when a fraction was presented before a decimal, the RTs (853ms) were shorter than when a decimal was presented before a fraction (1023ms). On the other hand, it is unlikely that the distance effect in the numerical comparison task was associated with the magnitude representation of denominators or numerators of fractions. If only the magnitude of denominator or numerator (1 or 5) was used to compare a fraction and a decimal successively presented (e.g., 1/5 and 0.3), participants would get the wrong answer by always reporting that the decimal was smaller than the components of the fraction.

The second important finding is that when the numerical distance was small (0.1 and 0.3, average 0.2), the distance effect appeared in the comparison task but not in the matching task. This finding is compatible with the results in two studies by Goldfarb et al. (2011) and by Gabriel et al. (2013b). In order to explore whether the distance effect depends on task paradigms, Goldfarb et al. (2011) compared the single-number processing in the comparison and matching tasks. They found a regular distance effect in the comparison task, but not in the matching task. Gabriel et al. (2013b) have compared the processing of fractions in a number comparison task and a number matching task using pairs of fractions. Results showed that the holistic representation of fractions was accessed in the comparison task but not in the matching task for both children and adults. The underlying reason for this finding may be that more numerical information is required in the comparison task than in the matching task (Gabriel et al., 2013b). When the task is matching between two digits, the task does not entail deep quantity processing in order to execute the correct response (Goldfarb et al., 2011). As a result, the distance effect, an indication of the numerical semantic representation, did not appear. In spite of no distance effect, however, it should be noted that fractions and decimals should be converted into a common representation in the matching task. Several recent studies have argued that the perceptual physical similarity between Arabic numbers other than the numerical distance contributes to the numerical processing in the matching task (e.g., Cohen, 2009; Defever, Sasanguie, Vandewaetere, & Reynvoet, 2012; Garcia-Orza, Perea, Abu Mallouh, & Carreiras, 2012; Wong & Szűcs, 2013). In this study, however, it was unlikely that participants transformed the fraction into a decimal using the semantic system, and then quitted using the semantic system and switched to a perceptual system for the comparison phase.

Interestingly, we found that when the distance was further apart (0.3 and 1.3, average 0.8), the distance effect appeared in the matching task, in contrast to no distance effect when the distance was small (0.1 and 0.3, average 0.2). This provides explicit evidence that fractions and decimals are converted into a common representation of magnitude in the matching task. When the numerical distance between a fraction and a decimal was too close, participants had difficulty discriminating between them. However, as in Experiments 3 and 4, pairs of a fraction and a decimal were further apart and they were more easily discriminated. Therefore, the numerical distance effect appeared. This finding reflects the fact that the magnitude representation of fractions and decimals is less accurate and coarse in the matching task. The less accurate representation of fractions and decimals should be closely associated with the nature of the matching task.

One possible framework that can deal with our findings in the matching task is the analyzer theory proposed by Treisman (1969). According to the analyzer theory, each attribute, such as color, size, or shape, is processed by a specific analyzer. Each analyzer is either opened or switched off responsive to the task demand (i.e., processes or does not process an attribute).When an analyzer is needed in order to fulfill a task, the analyzer will be opened and active while other irrelevant analyzers will be closed or inactive at least. Applying this theory to our study, when comparing two rational numbers, the numerical magnitude attribute analyzer is opened since it is necessary to give correct answers. However, in the matching task, the numerical magnitude processing is reduced by task demand, so the corresponding analyzer is not active. As a result, only a coarse representation of magnitude can be accessed which does not entail lots of processing resources. The coarse representation of magnitude makes it impossible for the appearance of distance effect when the numerical distances between fractions and decimals are small, as revealed by Experiment 2. Only when the numerical distances between fractions and decimals are bigger, the distance effect will appear, as revealed by Experiments 3 and 4.

In fact, our finding that the distance effect in the matching task only appeared when the distance was large is not the only one. In the study by Dehaene and Akhavein (1995), they found the distance effect in the matching task only based on analyses of the very small or very large digit pairs (1, 2, 8, and 9). In other words, the small distance was 1 and the large distance was very far ranging from 6 to 8, which is similar to our stimuli pattern in Experiments 3 and 4. Based on similar analyzes, this result was replicated by other studies (Ganor-Stern & Tzelgov, 2008; Goldfarb et al., 2011; Verguts & Van Opstal, 2005). However, when Goldfarb et al. (2011) analyzed the numbers 3, 4, 5, 6, and 7 which were not analyzed in Dehaene & Akhavein' s (1995) and Ganor-Stern & Tzelgov's (2008) study and did not appear in Verguts & Van Opstal's (2005) study, they did not find the distance effect in the matching task. Combining these findings based on integers, we can find that the representation of integers is also coarse in the matching task.

It should be noted that all our four experiments consistently demonstrated the order effect with shorter RTs for fraction first pairs than for decimal first pairs. This is a new finding that was not reported in the literature, suggesting that fractions were translated into decimals. The underlying reason may be that both comparison and matching tasks require representing one-dimensional values of magnitude. As suggested by DeWolf et al. (2015), fractions naturally express a two-dimensional relationship between two discrete sets; whereas decimals more naturally express the one-dimensional relative magnitude of a proportional relation. Therefore, previous studies have revealed easier and more efficient magnitude processing of decimals than fractions (e.g., DeWolf et al., 2014; Iuculano & Butterworth, 2011). Such finding is consistent with the learning difficulties associated with fractions and decimals.

Although decimals are typically introduced after fractions in school but they are generally mastered before fractions (Iuculano & Butterworth, 2011). In addition, fractions are not so common in everyday life as decimals. For all these reasons, participants tend to transform fractions into decimals. When tasks require relational reasoning, however, it is likely that decimals will be transformed into fractions. For example, in the study by DeWolf et al. (2015), it is more difficult when discrete () or discretized displays () are matched with decimals than when matched with fractions. One reason may be that fractions are advantageous in supporting relational reasoning with discrete concepts. In such cases, participants are likely to transform decimals into fractions.

Finally, this study observed the influence of context on the processing of fractions. We found that the same number pairs were responded to more slowly when mixed with small numerical distance pairs (0.10) as in Experiment 2, than when mixed with large numerical distance pairs (1.30) as in Experiment 3. This finding suggests that the processing of numbers is very flexible and adaptive to the experimental context (Huber et al., 2014; Ganor-Stern et al., 2011). We suggest that the perception of the distance between two numbers is affected by the other distance present in the task. We found that the performance of number pairs with a numerical difference of 1.30 did not differ between Experiments 3 and 4. This confirms that the influence of context is not related to specific numbers in a number pair, but linked to the numerical distance of the two numbers in a pair. Consistently, the same two numbers are responded to more slowly when presented in a larger number range than in a smaller number range (Pinhas, Pothos, & Tzelgov, 2013). In a larger number range, the context number pairs are responded to more slowly according to the size effect (Dehaene, 1992), that is, comparison of two numbers is harder for large than for small numbers (e.g., 8 and 9 vs.1 and 2). Therefore, the same two numbers are responded more slowly in a larger number range. This phenomenon is similar to the context effect with non-numerical magnitude comparisons (Čech & Shoben, 1985), which demonstrates that context has an effect on the ease with which people can determine the relative sizes of pairs of large and small animals. Typically, people are faster at choosing the larger of two large animals and the smaller of two small animals. However, when only pairs of small animals are presented the larger of these are treated as if they were large animals and are discriminated more rapidly under the choose larger instruction. Similarly, when only large animals are presented, the smaller of these are now treated as if they were small animals.

6. Conclusion

In summary, whether fractions and decimals share a common representation of magnitude is dependent on task paradigms. In the numerical comparison task, fractions and decimals could be translated into a common representation of magnitude. In the numerical matching task, fractions and decimals also shared a common representation. However, the representation of fractions and decimals was less accurate. As a result, the matching of fractions and decimals produced a significant distance effect only when the numerical distance was larger. In contrast, when the numerical distance was smaller, no distance effect appeared.

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The experimental pairs in Experiments 1, 2, 3 and 4

Experiment 1/2				Experiment 3				Experiment 4			
Small(0.1)		Large(0.3)		Small(0.3)		Large (1.3)		Small(0.3)		Large(1.3)	
1/5	0.3	1/5	0.5	1/5	0.5	1/5	1.5	5/4	0.8	1/5	1.5
2/5	0.5	2/5	0.7	2/5	0.7	2/5	1.7	5/4	0.9	2/5	1.7
3/5	0.5	3/5	0.3	3/5	0.3	3/5	1.9	6/5	0.8	3/5	1.9
7/5	1.3	7/5	1.1	7/5	1.1	7/5	0.1	6/5	0.9	7/5	0.1
8/5	1.5	8/5	1.3	8/5	1.3	8/5	0.3	7/6	0.8	8/5	0.3
9/5	1.9	9/5	1.5	9/5	1.5	9/5	0.5	7/6	0.9	9/5	0.5
1/2	0.6	1/2	0.2	1/2	0.2	1/2	1.8	8/7	0.8	1/2	1.8
3/2	1.4	3/2	1.2	3/2	1.2	3/2	0.2	8/7	0.9	3/2	0.2
1/9	0.2	1/9	0.4	1/9	0.4	1/9	1.4	9/8	0.8	1/9	1.4
2/9	0.3	2/9	0.5	2/9	0.5	2/9	1.5	9/8	0.9	2/9	1.5
1/8	0.3	1/8	0.5	1/8	0.5	1/8	1.5	7/8	1.1	1/8	1.5
1/6	0.3	1/6	0.5	1/6	0.5	1/6	1.5	7/8	1.2	1/6	1.5
7/4	1.6	7/4	1.4	7/4	1.4	7/4	0.4	7/9	1.2	7/4	0.4
1/3	0.4	1/3	0.6	1/3	0.6	1/3	1.6	8/9	1.1	1/3	1.6
2/3	0.7	2/3	0.9	2/3	0.9	2/3	1.9	8/9	1.2	2/3	1.9

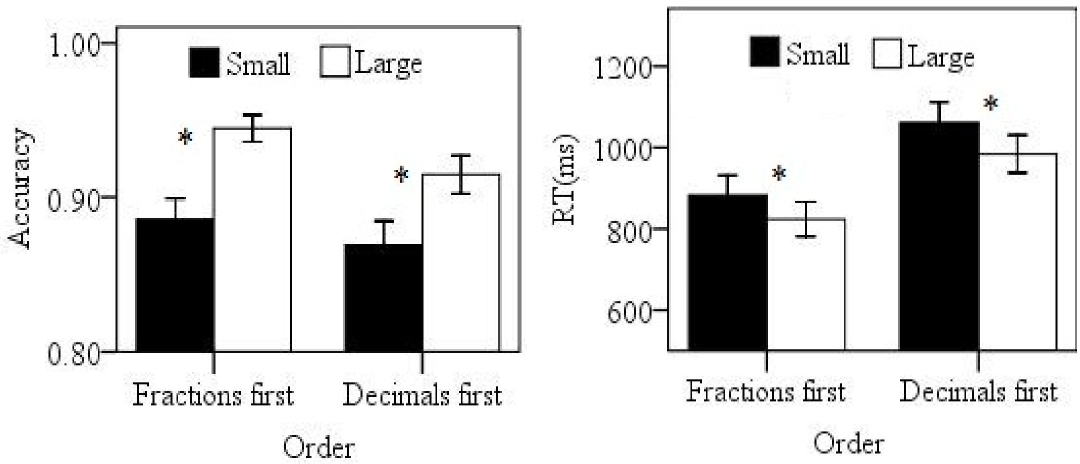

Figure 1. Accuracy and RTs as a function of order and distance in Experiment 1. Error bars indicate the standard error. Significant differences between the large and small distances at $p < .05$ were indicated by a *.

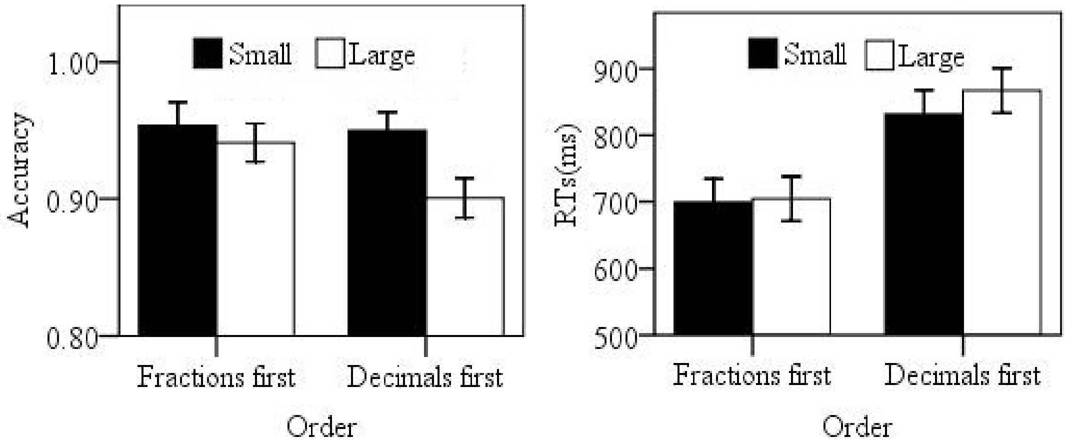

Figure 2. Accuracy and RTs as a function of order and distance in Experiment 2. Error bars indicate the standard error. No significant differences between the large and small distances were detected.

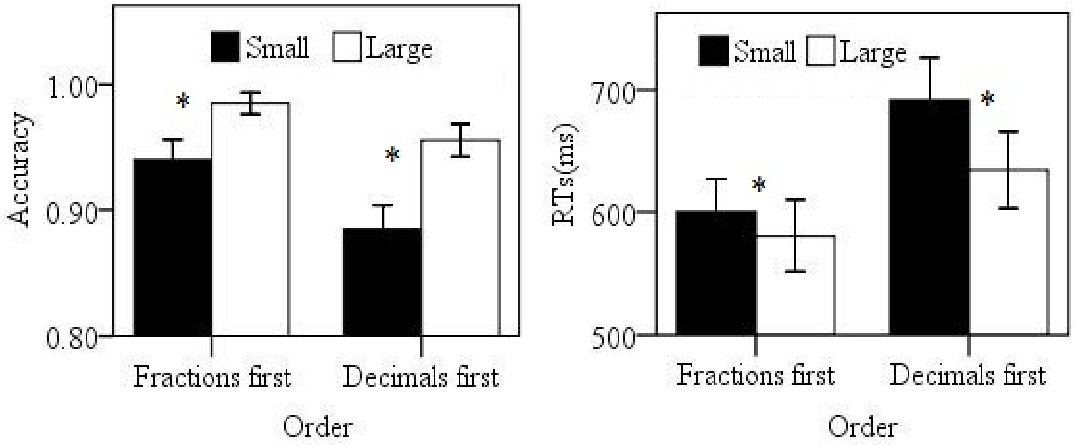

Figure 3. Accuracy and RTs as a function of order and distance in Experiment 3. Error bars indicate the standard error. Significant differences between the large and small distances at $p < .05$ were indicated by a *.

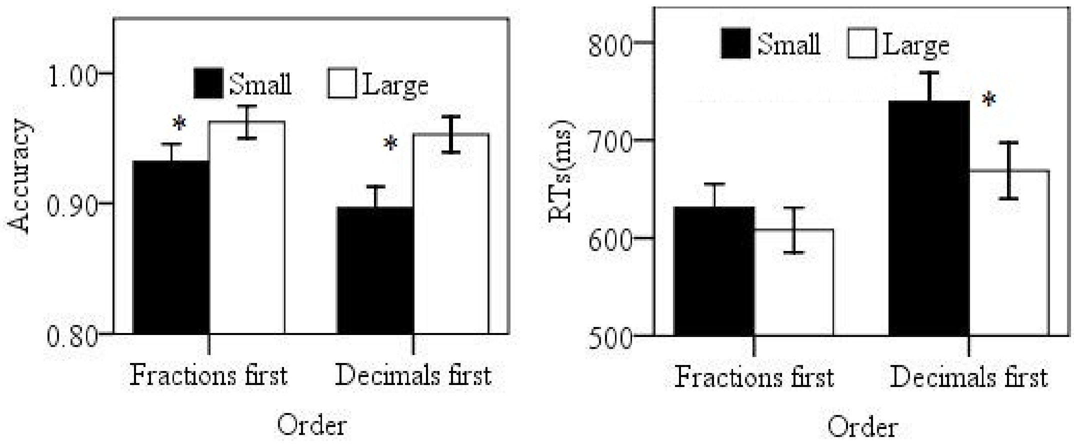

Figure 4. Accuracy and RTs as a function of order and distance in Experiment 4. Error bars indicate the standard error. Significant differences between the large and small distances at $p < .05$ were indicated by a *.